

# STATUS OF THE COMPRESSED BARYONIC MATTER (CBM) EXPERIMENT AT FAIR\*

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The CBM experiment at the Facility for Antiproton and Ion Research (FAIR) aims to explore the QCD phase diagram in the region of high net-baryon densities using nucleus–nucleus collisions ( $\sqrt{s_{NN}} = 2.9\text{--}4.9$  GeV). The CBM will be utilizing peak interaction rates of up to 10 MHz and an advanced triggerless data acquisition scheme to provide it with a unique access to rare physics probes required to accomplish CBM's physics goals. This contribution will summarise CBM's progress in terms of its physics performance simulations and the status of the comprising detector sub-systems, including their involvement in FAIR Phase-0 activities.

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## 1. Introduction to CBM-FAIR

The Facility for Antiproton and Ion Research (FAIR) [1] is a new particle accelerator facility currently under construction which aims to examine cosmic matter in the laboratory. The Schwer-Ionen-Synchrotron-100 (SIS-100) is at the heart of FAIR with heavy-ion beams to be injected from the existing SIS-18 ring accelerator at the GSI Helmholtz Centre for Heavy Ion Research in Darmstadt. The Compressed Baryonic Matter (CBM) experiment [2] is one of the four scientific pillars of FAIR and will utilise beams from SIS-100 (gold beams with kinetic energies between 2–11 A GeV;  $\sqrt{s_{NN}} = 2.9\text{--}4.9$  GeV) to study matter at conditions comparable to astrophysical objects and events [3]. Therefore, CBM's physics goals are centered to decipher the properties of Quantum Chromodynamics (QCD) matter at high net-baryon densities and to understand the equation-of-state of dense nuclear matter, the possible phase transition from hadronic-to-partonic phase, and chiral symmetry restoration. The respective physics observables include sub-threshold strangeness production, collective flow of emitted particles, excitation function of low-mass dileptons, and charm production among many

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others. A comprehensive review of CBM's physics goals and observables is presented in Ref. [4]. The CBM aims to access these 'rare probes' at up to 10 MHz high beam-target interaction rates by using a novel self-triggering, free-streaming, and radiation-hard readout electronics. These features are complemented by inspection of the full data stream in real-time to select and reconstruct events online.

The CBM is designed as a fixed-target experiment (depicted in Fig. 1) with an angular acceptance of  $2.5^\circ < \theta < 25^\circ$  and is capable of measuring hadrons and leptons in both their production channels. Located inside the superconducting dipole magnet, the Micro Vertex Detector (MVD) and the Silicon Tracking System (STS) are tasked to resolve the secondary vertex of short-lived open-charm mesons and provide momentum determination of charged particles, respectively. Dielectron identification is performed by the Ring Imaging Cherenkov (RICH) Detector with the UV photon detector planes based on Multi-Anode Photo Multiplier Tubes. Dimuon identification is done by the Muon Chamber (MuCh) System containing Gas Electron Multipliers and bakelite Resistive Plate Chambers sandwiched between hadron absorber plates. One of CBM's standout features is the interchangeability of RICH and MuCh, allowing the CBM to systematically measure dileptons in both production channels for the same detector acceptance. The Transition Radiation Detector (TRD) is also used for pion suppression, particle tracking, and identification of light nuclei and fragments via specific energy loss. Charged hadrons detection is performed by the Time-of-Flight (TOF) wall composed of Multi-Gap Resistive Plate Chambers (MRPCs) located about 7 m downstream. The Projectile Spectator Detector (PSD) is used to determine the collision centrality and reaction plane orientation.

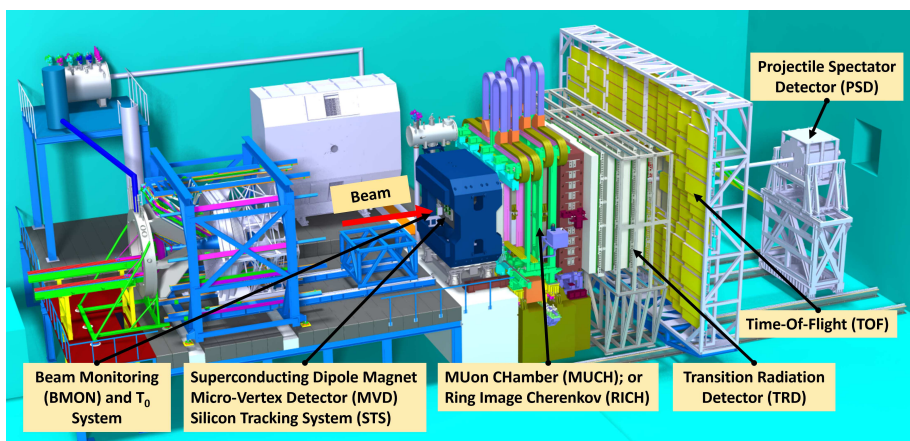


Fig. 1. CAD view of the CBM (right) and HADES experiment (left). SIS-100 beam will come from left to right of the image (Figure: P. Dahm, GSI Darmstadt).

## 2. Update on physics performance studies

The particle identification (PID) procedures developed for the CBM play a central role in benchmarking CBM's physics performance described in Subsections 2.1–2.3. The Cellular Automaton (CA) method based on track finder reconstructs charged particles' trajectories in the STS. This, in combination with the PID information from ToF and TRD, is used to further identify hadrons, light fragments and hypernuclei under the **Kalman Filter Particle Finder (KFPPF)** package. This is further complemented by collision centrality determining methods by using charged particle multiplicities in STS and the energy of spectator fragments to provide a complete picture of the underlying collision.

### 2.1. Hadrons and strangeness

Tools for the multi-differential physics analysis have been prepared for doing a comprehensive analysis of strange hadrons and hypernuclei (see Fig. 2 (left)). Further optimisation of reconstruction yields of  $K_s^0$ ,  $\Lambda$ , and  $\Xi^-$  have been done by using Machine Learning (ML) techniques to successfully demonstrate high signal purity and efficient rejection of the combinatorial background by  $> 40\%$  for the same efficiency (see Fig. 2 (right)). Additionally, CBM's capabilities to reconstruct the proton's transverse momentum spectrum within 5% systematic error for different underlying EoSs in the Three-fluid Hydrodynamics-based Event Simulator (THESEUS) have been shown.

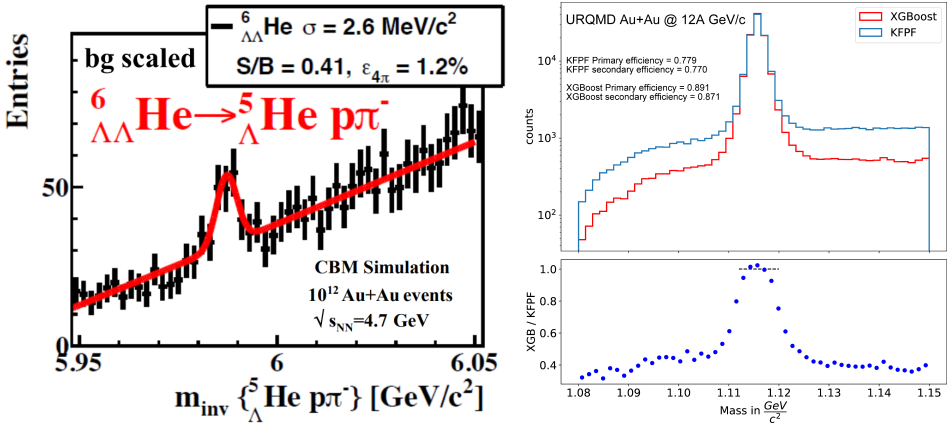


Fig. 2. (Colour on-line) Left: Reconstructed invariant mass distribution of double  $\Lambda$  hypernuclei —  ${}^6_{\Lambda\Lambda}\text{He}$  (Figure: I. Vassiliev, GSI Darmstadt). Right: Comparison of  $\Lambda$  invariant mass distributions for particle selection criteria based on KFPPF in black/blue and XGBoost Machine Learning Model in grey/red (Figure: S. Khan, ECU Tübingen).

## 2.2. Correlation, flow, and fluctuation

Multi-differential analysis of the  $v_1$  flow harmonic for  $K_s^0$ ,  $\Lambda$ , and  $\Xi^-$  hyperons have been performed as a function of rapidity and transverse momentum for different centrality classes. This flow analysis is further complemented with feasibility studies using multiparticle azimuthal correlations. This analysis is challenging due to CBM's fixed-target geometry and energy range (non-uniform acceptance and low multiplicities), but feasibility in terms of symmetric cumulants ( $SC(m, n)$ ) was successfully shown (see Fig. 3 (left)). Feasibility studies to conduct measurements of proton–proton and pion–pion correlations via femtoscopic measurements have also been performed. Further femtoscopic analysis with higher statistics and realistic cuts is ongoing for precise reconstruction of source properties.

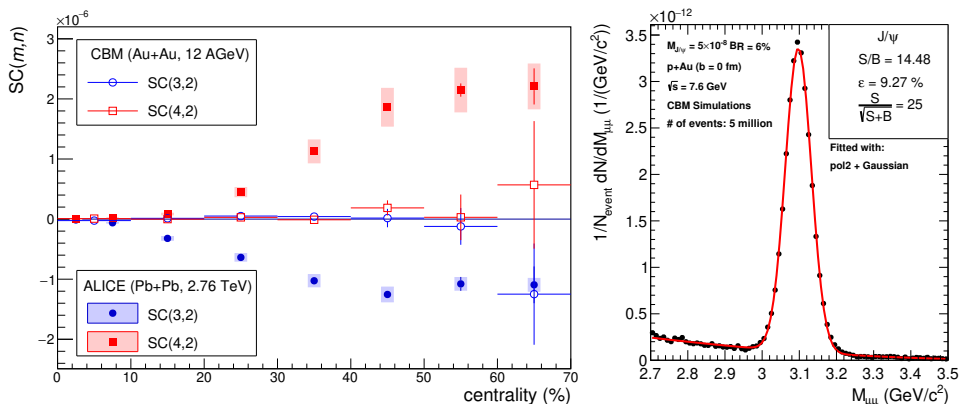


Fig. 3. Left: Variation of symmetric cumulants ( $SC(3,2)$  and  $SC(4,2)$ ) with centrality and their comparison with ALICE measurements (A. Bilandzic, TU München). Right: Reconstructed  $J/\psi$  invariant mass spectra with  $(\sigma_M(J/\psi) = 35 \text{ MeV}/c^2)$  at  $\sqrt{s_{NN}} = 7.6 \text{ GeV}$   $p+Au$  collision (Figure: S. Chatterjee, Bose Institute Kolkata).

## 2.3. Dileptons

Performance studies, in terms of reconstruction of freeze-out cocktail have been done for dileptons (in both production channels  $e^+e^-$  and  $\mu^+\mu^-$ ) with realistic detector geometries, material budget, and response over the entire SIS-100 energy range. This has allowed to access the underlying thermal signal and reconstruct clear peaks for the low-mass vector mesons ( $\sigma_M(\omega) = 14 \text{ MeV}/c^2$ ) with a pair detection probability of  $\approx 10\%$ . A particular emphasis has also been placed on using sub-threshold charmonium measurements to study cold nuclear matter effects of  $p+A$  collisions and to study pQCD-inspired models at low energies (see Fig. 3 (right)).

### 3. Detector updates and FAIR Phase-0

Almost all CBM detector sub-systems have completed their R&D phases, with their Technical Design Reports available in Ref. [5]. MVD has shown production readiness for the pre-production sensor version. The engineering and production readiness of various STS components was reviewed for pre-production to start in late 2022. The MuCh has built and tested real-size GEM and RPC chambers, and has conceptually reviewed their mechanical aspects. RICH has accomplished its “first of series test” for their electronics and is constructing a full-size photo-camera demonstrator. The TRD has submitted the proposal for their inner high-rate inner modules with novel 2D readout pads. The TOF has undertaken an extensive campaign to determine their rate limits and mitigation efforts towards observed aging are ongoing. Technical designs of the target mechanism, beam pipe, and beam monitors have been developed. Evaluation of the impact on the project of sanctions imposed on Russia, especially regarding the superconducting dipole magnet, the PSD and the CBM’s timeline is presently ongoing.

Different aspects of the CBM have been continued to be thoroughly tested in FAIR’s precursor programme — FAIR Phase-0. The 2021 campaign of mCBM@SIS-18 at GSI [6] has successfully demonstrated the triggerless-streaming readout and data transport of the CBM with a setup composed of prototype components of all CBM’s detector sub-systems with the readout chain interfaced with the Common Readout Interface (CRI) boards (see Fig. 4). Moreover, detailed high-rate tests have been performed for radiation tolerance validation of various sub-system’s components. Other FAIR Phase-0 activities include: (i) the successful implementation of CBM’s KFPF package in STAR’s express analysis chain and endcap Time-of-Flight (eTOF) comprising 36 CBM-TOF modules for the BES-II campaign [7, 8]; (ii) HADES-RICH upgrade with 428 MAPMTs from CBM-RICH [9].

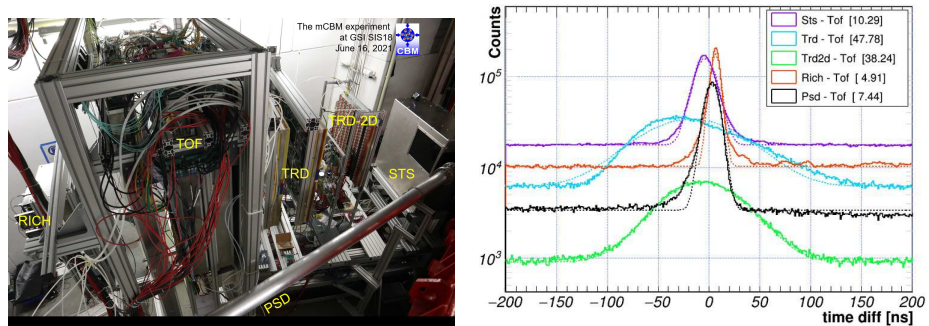


Fig. 4. Left: mCBM setup for the 2021 campaign (Figure: C. Sturm, GSI Darmstadt). Right: Time synchronicity between all sub-systems for O+Ni collisions at 2.0 A GeV at about 1 MHz collision rate (Figure: A. Weber, JLU Giessen).

#### 4. Conclusion and outlook

The CBM, with its foreseen capabilities can map out the high-density region of the QCD phase diagram by studying conditions similar to the core of neutron stars and can help usher a new era of multi-messenger physics. This is substantiated by the recent physics performance studies focusing on the rare probes required to achieve this goal. All detector sub-subsystems are progressing well towards the strategic objective to be ready for series production. The active participation in FAIR Phase-0 has contributed substantially to CBM's understanding of the underlying sub-systems. The mCBM after verifying CBM's readout concept is currently undertaking benchmark runs targeting  $\Lambda$  baryon reconstruction in Au+Au collisions at 1.24 A GeV and Ni+Ni collisions at 1.93 A GeV.

The CBM experiment is being developed by a collaboration consisting more than 400 persons from 47 institutions and 11 countries. The CBM is supported by national funding agencies of the CBM member institutions. The author acknowledges the support from the German Federal Ministry of Education and Research (Project-ID 05P19VTFC1) and the Helmholtz Graduate School for Hadron and Ion Research (HGS-HIRe).

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